Non-Linear Problems in Ocean Engineering: On the Evolution of Energetic Ocean Waves and Their Interaction With Structures

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Grant #: N00014-97-1-0039

LONG-TERM GOALS

Improve and develop new scientific understanding of non-linear waves, including effects of wind and breaking, and the effect of non-linearities on wave evolution and wave impact on structures.

OBJECTIVES

(1) To understand and simulate the role of wind, currents, and wave breaking on the long-term evolution of wave systems, including discretization, wave group formation, downshifting, directional distribution of energy, and the generation of extreme waves.

(2) To understand and simulate the morphology of deformed and breaking waves, and breaking onset.

(3) To understand and simulate impulsive loading and hydroelastic response of ocean structures due to breaking wave impact. (Completed)

APPROACH

(*Numbers refer to Objectives*)

(1) Wave evolution experiments in the large Ocean Engineering Laboratory tank, including wind. (Remy). Numerical simulations utilizing a range of evolution models (fully non-linear, spectral, NLS). Theoretical development of evolution equations utilizing the Lagrangian (variational) method. (Tulin, Li).

(2) High-resolution (2d+t) numerical simulations (both progressive and ship waves). (Fontaine). Wave tank observations, including surface particle measurements, (Matsiev), and radar measurement. (Fuchs). Theory of breaking inception. (Tulin).

(3) Observations and tank measurements on hydroelastic models; numerical simulation and comparison with experiment (slamming); theoretical analysis (loading on curved structures).

WORK COMPLETED

(1) Extensive tank experiments on the non-linear evolution of water waves have been completed: (i) on wave group evolution, including breaking effects; Publication 1; (ii) on the effect of wind on unstable evolution; Publication 2; (iii) on the rapid evolution of heavily breaking wave systems. All by Tulin, Waseda

Theoretical analysis of the stability of ocean-like wave systems with energy continuously distributed in direction; Publication 3. By Tulin, Li.

Theoretical development and application of evolution equations utilizing the Lagrangian (variational) method, including the effects of wind and wave breaking, Publication 6. By Tulin, Li.

Extensive measurements and analysis of wind wave evolution including directionality have been made in the large OEL wind wave tank and compared with field measurements. By Remy, Tulin.

(2) Extensive tank observations of breaking and post-breaking have been made and compared with earlier numerical simulations, Publication 1, and in Ref. C. Numerical simulation of wave group evolution until breaking, to determine the breaking boundaries; Publications 1 and 5. Landrini, Waseda, Oshri, Tulin.

The development of an optical system for the measurement of surface velocities (3d.) in wave systems, including wind waves, has been completed and used. Extensive measurements of orbital and drift velocities have been made and utilized to validate earlier numerical simulations of wave breaking. The OEL breaking criterion has been confirmed experimentally. Publications 7 and 8. Matsiev, Hoyer, Tulin.

(a) An analytic proof has been derived of the OEL criterion for the inception of breaking of modulated energetic waves, Ref. 7, Tulin.

(b) The evolution and destruction of microbreakers (25-75 cm. length) has been studied utilizing photography, wave wires, and radar, Publication 9. Extensive tank measurements were completed of the hydroelastic response of an elastic vertical cylinder mounted in the OEL wind-wave tank, subject to loading by monochromatic waves and wave groups, and the last paper was published in December 1999, Publication 4. By Welch, Levi, Fontaine, Tulin. An analysis of loads on curved structures was published in 1999, Publication 10 (partial support). By Miloh, Galper. Extensions of the 2d+t method and applications were proposed and published, Publication 11, 12 and 13. By Fontaine, Tulin. Hydroelastic scaling was analyzed. Publication 14.

(Other) Extensive work earlier carried out for ONR-Ocean Engineering, on internal waves generated by ships, has been published, Publication 15.

RESULTS

Wave Evolution. A series of important discoveries and developments have been made: (a) wave breaking plays a primary role in wave downshifting and fundamentally alters wave-wave inviscid interactions; both occur on similar time scales; (b) wind pumping plays a secondary role in wave stability and downshifting; (c) wave instability and near-neighbor wave-wave interactions cause discretization of wave systems, both mechanical and wind wave; (experimental result) (d) continuous downshifting can be understood as a series of breaking cycles involving the interaction at any instant between two closely spaced waves which contain the bulk of the wave energy; (e) evolution equations including the effect of wind pumping and breaking dissipation can be developed rigorously from basic considerations utilizing the variational approach, introducing a work function to represent the effect of wind and breaking; (f) the evolution equations developed in this way can be put in the form of the non-linear Schrodinger equation, but now extended to include the effect of wind pumping and breaking; (g) wind wave evolution in the large OEL wind-wave tank (fetches over 100ft.) is very similar to evolution on a much larger scale in the field; (h) spectral discretization in both frequency and direction has been discovered at all fetches in the large wind-wave tank in both wave wire arrays and radar measurements; and (i) the evolution of wind-generated microbreakers has been experimentally observed to end with their destruction when passing through energetic breakers a few meters long.

Wave Breaking. Our work under this contract has led to an understanding of breaking and its inception. The following picture has emerged: (a) deep water breaking is a consequence of wave modulation; (b) breaking is proceeded by the interruption of sinusoidal wave propagation at the peak of a wave group and the successive deformation of the wave, leading to the creation of a jet at the wave crest; (c) a simple and consistent criterion exists for the interruption of the sinusoidal motion; (d) this criterion is that the wave orbital velocity at the wave crest exceeds the group velocity (this has now been confirmed by actual measurements); (e) the front face of a strong breaker assumes a parabolic shape; (f) the jet falls in a ballistic trajectory, impacting, and creating a secondary forward splash and associated vorticity; (g) breaking can occur for wave steepnesses, ak (based on the average wave energy in the modulated wave) down to about 0.1, consistent with ocean measurements; and (h) the breaking criterion is a consequence of kinematical requirements on the particle velocity as the wave crest passes through the peak of the wave group.

Ringing. This phenomenon has been shown, as a result of our experimental work, to be the result of impact by a deformed and breaking wave, and a correlation between impact loading and the local slope of the wave at the cylinder was found.

IMPACT/APPLICATIONS

We have already earlier applied some of our results on the relation between wave downshifting and breaking dissipation to the prediction of the fetch laws, with very satisfactory results, Ref. A. Now, we have confirmed these earlier results experimentally. This means that existing methods of predicting downshifting in use in most wave forecasting programs worldwide which ignore the influence of breaking, are not soundly based and should be revised. Our recent mathematical development, starting with the variational formulation, provides a beginning basis for a rigorous method of predicting evolution, including both wind pumping and breaking. The specification of the directional distribution of energy remains to be soundly based. Our recent work, Ref. 3, on the instability of directionally spread spectra is an important step in that direction.

Our recent development of evolution equations, including downshifting, allows for the prediction of small-scale oceanographic events, including effects of wind unsteadiness. We have already applied these results to the prediction of extreme waves following the passage of line squalls, Ref. B.

Our results on wave morphology are now widely used by radar scattering theorists and have already led to a relatively simple explanation of sea spikes, Ref. C.

Our experimental discovery of the discretization of wind wave systems (which is similar to discretization in mechanical wave evolution) casts doubt on the usual stochastic description of wind waves, which assumes a continuous spectrum, and sooner or later, this discretization must be explored for ocean waves.

Our results on wave impact loading, combined with results on wave morphology provide a direct way to predict the occurrence and severity of such loading in a given seastate.

It is clear that breaking signatures play a huge role in remote sensing of both the perturbed ocean surface, and ship waves. Our discovery of the criterion for breaking provides a basis for the prediction of changes in breaking pattern due to weak currents, etc., and therefore for remote sensing signatures.

TRANSITIONS

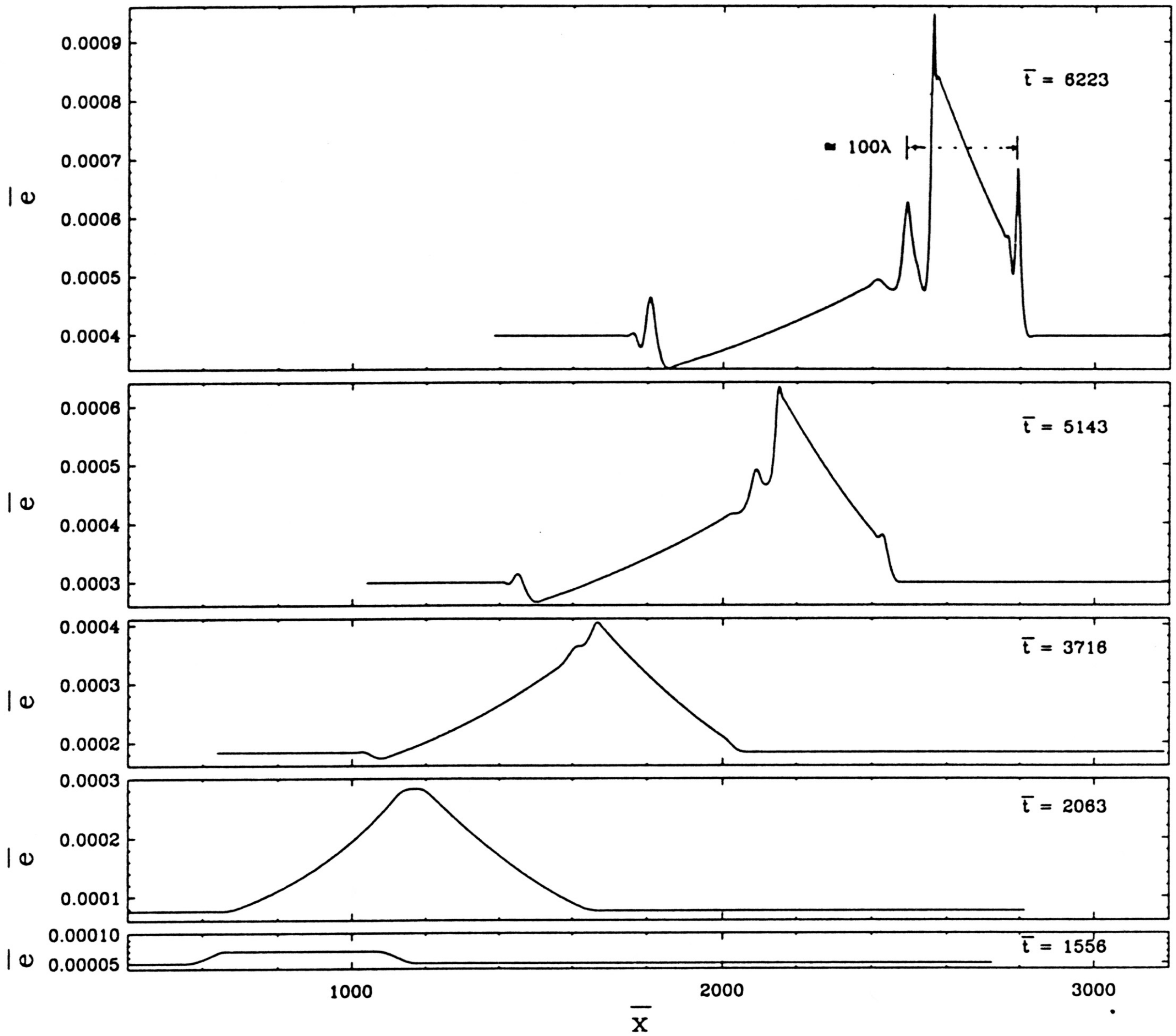
- Specific breaking wave morphology histories produced here are in wide use by Navy contractors and others as benchmarks for the calculation of radar scattering from breaking waves (NRL, Oklahoma State, RDA, and others).

- Our breaking criterion is used as the basis for the prediction of remote sensing signatures due to sea surface perturbations (RDA).

- Our evolution equations including wind and breaking effects have been used to predict the generation of extreme waves due to line squalls (OEL), and for the prediction of the fetch laws (OEL).

- Our breaking wave morphology has been used as the basis for the explanation of measured seaspike (radar) anomalous returns, when combined with ray based scattering theory (OEL).

- Our 2d+t method for the calculation of bow breakers on ships is now being extended to include the post-breaking phase and applied in a systematic way (OEL with ONR support).



Extreme waves (upper right at $\bar{x} \approx 2500$), appear after a squall has blown up a localized patch of waves higher than the background ($\bar{x} \approx 1000$).

Simulated using our non-linear evolution equations. Wave energy ($\bar{e}$) .